

Future Physics Capabilities of RHIC

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Abstract.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is a versatile facility for both heavy-ion and polarized-proton collision physics. The initial heavy-ion runs (Au+Au, Cu+Cu, and d+Au) have led to the unexpected discoveries at RHIC that (1) the new state of matter produced is a “nearly-perfect” fluid, (2) fast quarks (jets) lose large amounts of energy, when traversing the medium, (3) the quarks themselves are observed to flow, and (4) forward particle production is lower than expected. The polarized proton (p+p) program has discovered that gluons do not make a maximal contribution to the spin of the proton. Substantial upgrades to the accelerator and experimental detectors are ushering in an exciting transition from discovery to understanding. RHIC is poised to address these fundamental questions of broad significance: (a) What are the phases of QCD matter? (b) What is the wave function of the proton? (c) What is the wave function of a heavy nucleus? (d) What is the nature of non-equilibrium processes in a fundamental theory? After a brief introduction this talk and paper give an abbreviated overview of what has been learned so far, the plan for the mid-term (2006-2011), and the long-range plan (2012 and beyond).

The outline for this talk and paper is:

1. Introduction
2. What have we learned so far?
3. RHIC Plan for the Mid-Term: 2006-2011
4. RHIC plan for the Long-Term: 2012-...

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) was named for its ability to collide heavy ions (e.g., fully-stripped gold nuclei) at relativistic velocities with maximum center of mass collision energies up to $\sqrt{s_{NN}} = 200$ GeV. RHIC is also the world’s only polarized-proton collider with a maximum p+p collision energy of $\sqrt{s} = 500$ GeV. Continual development of RHIC and the Alternating Gradient Synchrotron (AGS) have led to impressive gains in facility performance and confident projections for significantly enhanced future capabilities. Technical descriptions of RHIC and the four experiments are provided elsewhere [1]. Overviews from each RHIC Collaboration on the results from the first three years were published [2, 3, 4, 5] and announced at the April APS Meeting in Tampa, Florida [6]. The discovery that the matter produced at RHIC was observed to be a “nearly-perfect” fluid was later chosen by the American Institute of Physics as the top news story of 2005 [7]. Science Working Groups were formed in 2004 to develop the physics case for *Future Science at RHIC*, for which the latest update was released on December 30, 2006 [8].

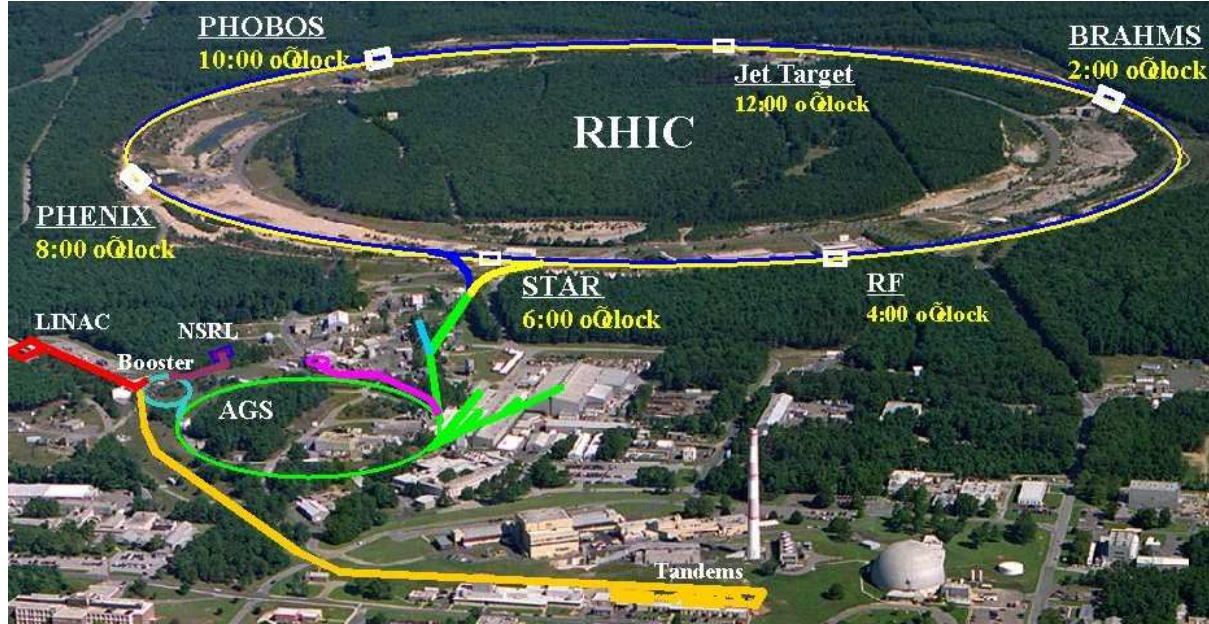


Figure 1. Aerial photograph showing the transfer lines for heavy ions from the tandems (lower center) and for polarized protons from the LINAC (left center), both of which then travel through the Booster Synchrotron, the AGS, and up to RHIC, where ion bunches are alternately injected into separate rings to travel clockwise or counterclockwise toward and through six possible collision regions.

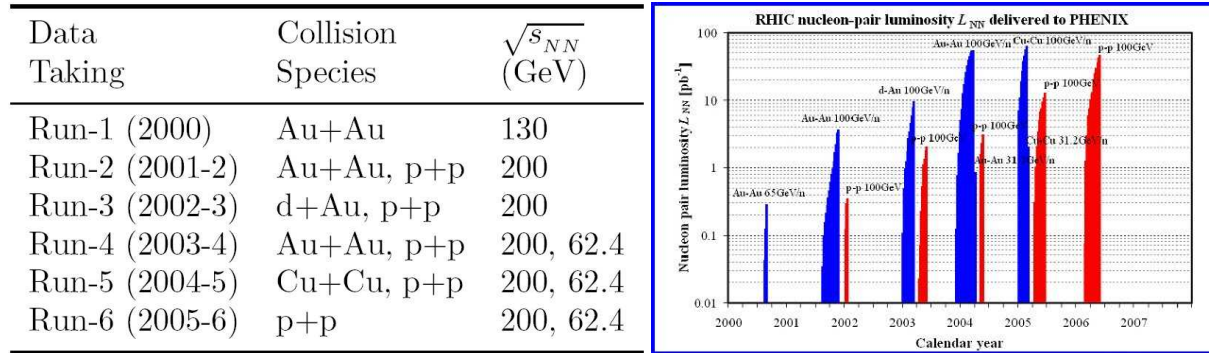


Figure 2. (left) Species collided at RHIC; (right) Yearly increasing performance at RHIC.

Figure 1 shows an aerial view of the RHIC & AGS facility and the locations of the four original detectors: BRAHMS, STAR, PHENIX, and PHOBOS. The two smaller experiments concluded operation in 2005 (PHOBOS) and 2006 (BRAHMS), while the two larger experiments, PHENIX and STAR, plan to continue operation into the distant future. Also shown is the location of the Jet Target (12:00 o'clock), which is used for measurements of the proton beam polarization.

Figure 2 shows the RHIC species during the first six runs (2000-2006) and the RHIC performance plotted, for example, as the nuclear-pair luminosity, L_{tot} delivered to the PHENIX experiment. Note that the integrated luminosities increase substantially each year and that Run-6 had only p+p collisions due to funding delays and funding limitations.

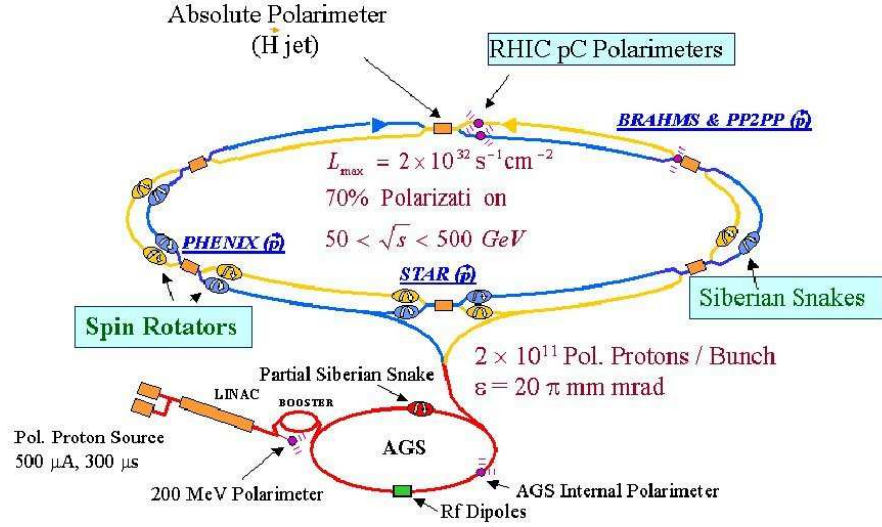


Figure 3. Locations at RHIC of polarimeters, spin rotators, and Siberian snakes for polarized p+p collisions.

Figure 3 illustrates the key components of RHIC when used as a polarized proton collider. In addition to the yearly increases in p+p luminosity shown in Fig. 2, there have also been yearly increases in polarization. Both are essential for the success of the spin program, especially because the figure of merit is the polarization to the fourth power times luminosity, P^4L , for double longitudinal asymmetry measurements (e.g., [9]).

2. What have we learned so far?

The *Future Science at RHIC* document [8] summarizes and reviews what we have learned so far. The first five years of RHIC operation have resulted in the discovery of a new form of thermalized matter produced in Au+Au collisions at energy densities more than 100 times that of a cold atomic nucleus. Comparisons with relativistic hydrodynamic models indicate that the matter thermalizes in an unexpectedly short time (less than 1 fm/c), has an energy density at least 15 times larger than needed for color deconfinement, has a temperature about 2 times the critical temperature of 170 MeV predicted by lattice Quantum Chromodynamics (QCD), and appears to exhibit collective motion with ideal hydrodynamic properties – a “perfect liquid” that appears to flow with a near-zero viscosity to entropy ratio – lower than any previously observed fluid and perhaps close to a universal lower bound. Figure 4 illustrates the enormous collective motion of the medium, pointing to rapid thermalization and strong coupling of the matter produced at RHIC.

The newly discovered form of matter is found to directly involve quarks. Comparison of measured relative hadron abundances with very successful statistical models indicates that hadrons chemically decouple at a temperature of 160-170 MeV. There is evidence suggesting that this happens very close to the quark-hadron phase transition, i.e. that hadrons are born in the phase transition from quark matter, and abundance-changing interactions then quickly cease. Valence quark number scaling of the measured anisotropy parameter for all hadrons suggests that the collectively flowing matter involves quarks, not hadrons. And the striking observation of a universal, strong enhancement of baryons relative to mesons at intermediate transverse momentum has been interpreted as evidence of competition between quark coalescence of the bulk medium and jet fragmentation. Figure 5 illustrates jet quenching, observed via the suppression of particle production at high transverse momenta and the dramatic modification

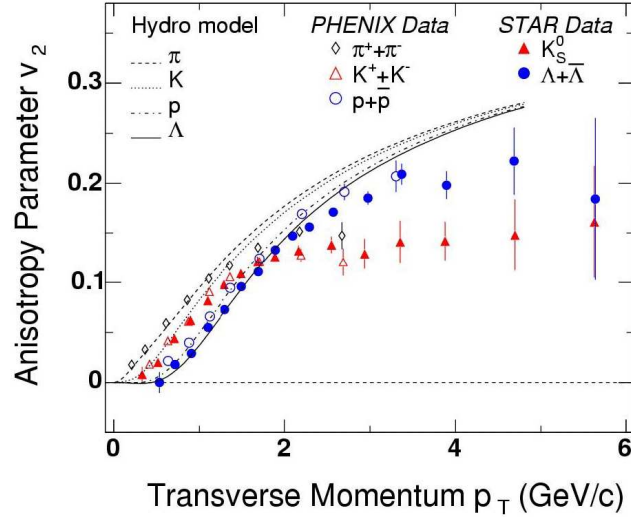


Figure 4. Elliptic flow (v_2) plotted as a function of transverse momentum (p_T) for identified hadrons. The elliptic flow is a measure of the anisotropic pressure-driven expansion in off-center collisions. The compilation of STAR and PHENIX data is compared with hydrodynamic predictions. Note that the bulk of the particle production is at less than 2 GeV/c. Hydro is expected to break down at $p_T \gtrsim 1.5$ -2 GeV/c.

of jet correlations in central Au+Au collisions, pointing towards dramatic energy loss of partons traversing matter of very high color charge density. Note the strong suppression of the mesons and the lack of suppression for the photons (γ), which do not interact with the final state medium.

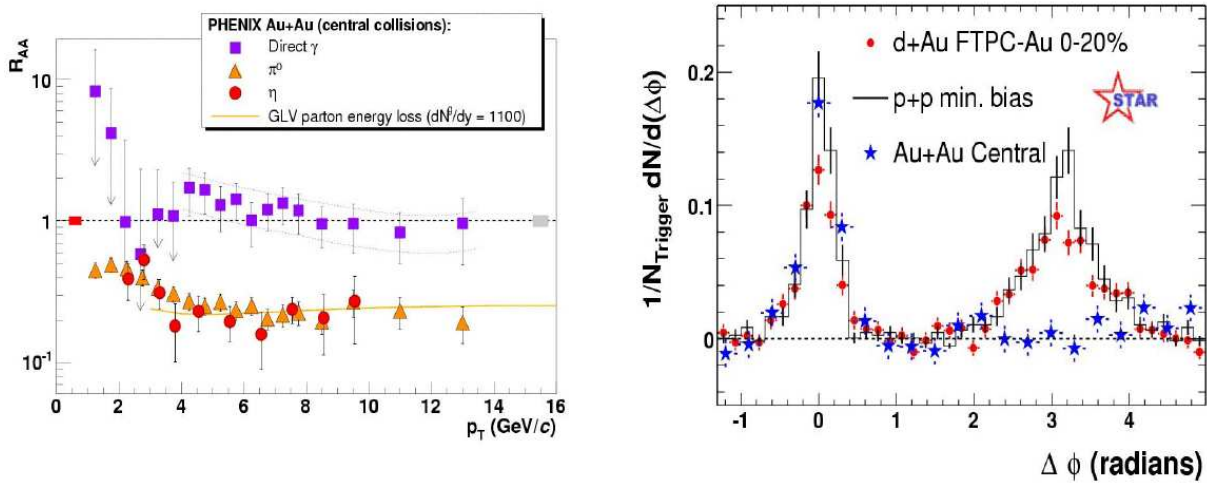


Figure 5. The nuclear modification factor, R_{AA} , is the ratio of the cross section per nucleon-nucleon collision measured in a heavy ion collision divided by the cross section measured in pp. If there were no nuclear effects it would be unity. (left) $R_{AA}(p_T)$ for γ , π^0 , and η in central Au+Au collisions. (right) Correlations in azimuthal angle between high momentum hadrons showing evidence of suppression of back-to-back jets in central Au+Au relative to p+p and d+Au collisions.

The new matter at RHIC is not describable in terms of ordinary color neutral hadrons. Many observations are consistent with models that incorporate quark and gluon degrees of freedom. The evidence is consistent with the matter being a strongly coupled quark gluon plasma (sQGP), and thus it behaves quite differently from the perturbative QCD parton gas that was expected by most people prior to RHIC data. The extraordinary properties of this new state of matter demand further measurements to better understand its behavior, properties, origin and description. Figure 6 illustrates the large, anomalous enhancement of baryon and anti-baryon production rates at intermediate transverse momentum relative to mesons, together with scaling of hadron production yields and their collective motion with the number of valence quarks, suggesting that hadrons form by quark coalescence after the flow occurs.

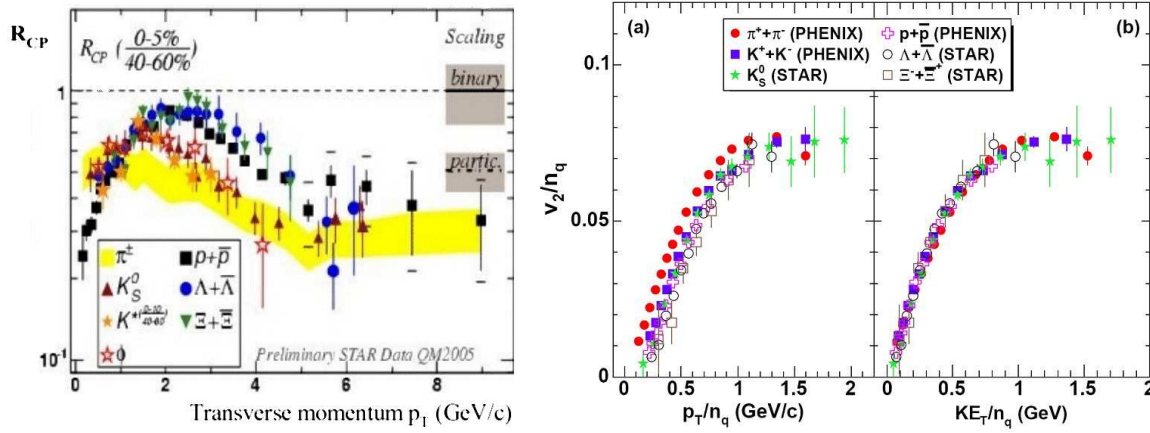


Figure 6. (left) The nuclear modification factor R_{CP} is the ratio of cross section per nucleon-nucleon collision in central events to that in peripheral events. STAR and PHENIX $R_{CP}(p_T)$ data for identified hadrons shows the Note the two separate bands for baryons and mesons. (right) The elliptic flow parameter plotted as v_2 per quark vs. p_T and transverse energy, KE_T , per quark [10, 11, 12] The scaling with the number of valence quarks is clearly shown.

The RHIC program has also found unexpectedly low multiplicities of produced hadrons in heavy ion collisions and suppression of high transverse momentum particles in the forward direction in d+Au collisions, both of which are consistent with gluon saturation in the colliding nuclei playing an important role at RHIC energies. The saturation scale represents a fundamental property of hadrons and nuclei, and so it is essential that we determine if gluon saturation is the correct explanation for the existing RHIC data. This will be addressed prior to the major accelerator upgrade project (RHIC II) by new capabilities provided by detector upgrades, after which the higher RHIC II luminosities will enable powerful, detailed tests of theory using measurements with rare probes. Figure 7 shows the first indications of gluon saturation in heavy ion collisions, as evidenced by reduced total particle production at RHIC energies.

Finally, the world's first polarized proton collider has been commissioned at RHIC, and the task of trying to understand the spin structure of the proton has begun. The RHIC spin goals include direct measurements of the gluon and flavor-separated quark and antiquark contributions to the proton's spin, and studies of the transverse spin and transverse motion preferences of the quarks and gluons in a transversely polarized proton. These goals will be met by a series of precision measurements using processes that can be understood well using pQCD. These measurements require very large integrated luminosity, but they have huge potential to resolve the long-standing puzzle of the origin of proton spin in terms of its constituents.

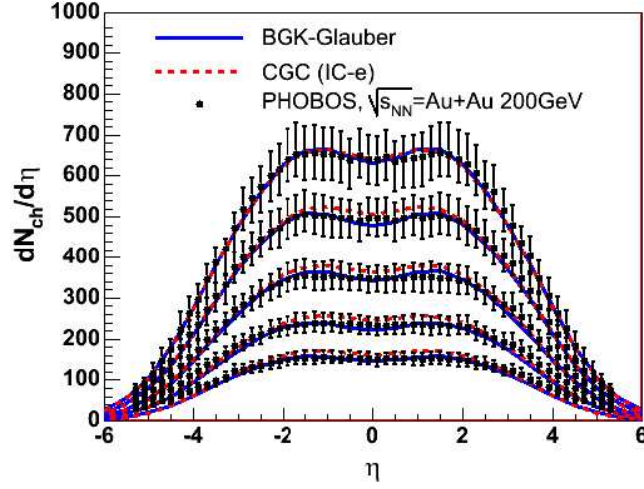


Figure 7. PHOBOS data on $dN_{ch}/d\eta$ as function of rapidity, η , for variety of collision centralities, together with a fit using the Color Glass Condensate model, in which the saturation of the density of gluonic matter in the initial state leads to lower than expected particle multiplicity for central Au+Au collisions at RHIC energy.

Figure 8 shows recent spin physics results from STAR and PHENIX. The STAR results for single-spin transverse asymmetries demonstrate that sizable spin effects can be observed in hadronic collision regimes where pQCD is applicable. The PHENIX results on two-spin longitudinal asymmetries rule out extreme scenarios in which gluon polarization would account, even at low momentum transfer scales, for greater than 100% of the proton spin, only to be partially compensated by orbital contributions.

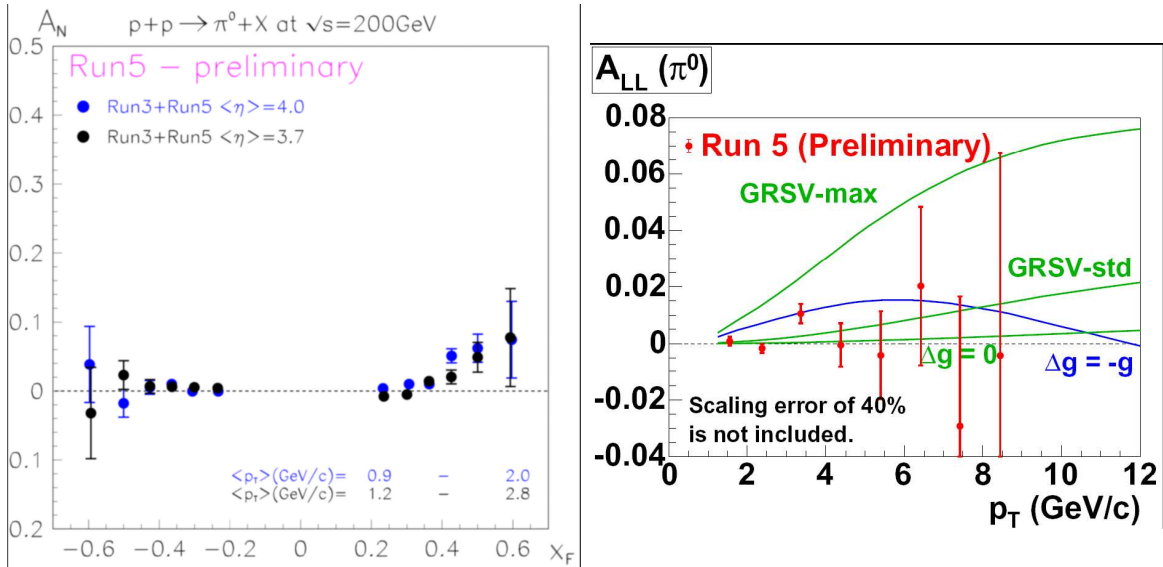


Figure 8. (left) STAR results for transverse single-spin asymmetries for inclusive forward π^0 production, showing their dependence on $x_{Feynman}$. (right) PHENIX results for the two-spin longitudinal asymmetry for mid-rapidity inclusive π^0 production, compared to next-to-leading-order pQCD calculations assuming various scenarios for gluon polarization.

The exciting and unexpected discoveries at RHIC provide strong impetus for future exploration. What we have learned so far in the heavy-ion physics program raises questions that produce compelling needs for further understanding:

1. The new state of matter is a “nearly-perfect” liquid. *What are the properties of the RHIC liquid? Why does it behave the way it does?*
2. Fast quarks (jets) lose large amounts of energy. *Can we use these jets to take a “picture” of the collision? How does the energy loss happen?*
3. The quarks themselves are observed to flow. *What pressure drives this flow? Are the quarks flowing individually? Do they bind together with other quarks and gluons?*
4. Forward particle production is lower than expected. *Do gluons form a glass-like state in the early stages of heavy-ion collision dynamics?*

Addressing these important questions and advancing the spin-physics program requires upgrades to the accelerator facility and the detectors at RHIC.

3. RHIC Plan for the Mid-Term: 2006-2011

While recent delays in determining the FY 2007 budgets may alter the timelines, the Mid-Term Strategic Plan for RHIC was released in February of 2006 [13]. In the quest for higher luminosity and polarization, more flexibility, and increased uptime, a number of upgrades are planned for the next few years:

- a. The evolution towards the enhanced luminosity and polarization goals
- b. The construction of the new ion injector EBIS
- c. The development and implementation of electron cooling for RHIC II
- d. Improvements to infrastructure
- e. Design of the electron-ion collider eRHIC

Specific actions related to each of the above are: (a) For both the proton luminosity and polarization goals, the AGS cold snake needs to be fully commissioned. For heavy ions, longitudinal stochastic cooling is being pursued to increase the average store luminosity by up to 50% and to reduce the experimental background. (b) The new Electron-Beam Ion Source EBIS replaces the 35-year old Tandem electrostatic accelerators. Not only will the EBIS be simpler and more reliable with lower operating costs, but new species can be offered such as uranium and polarized He-3. (c) Electron cooling at RHIC is based on a high-intensity, low emittance superconducting electron gun, and an Energy-Recovery Linac (ERL), also superconducting. (d) Mature components must be replaced to maintain reliability and performance. These upgrades will be phased in as funding and running times permit. (e) The plans for eRHIC will be addressed in the next section.

To address the compelling physics questions noted above, PHENIX and STAR each have a suite of upgrades that are planned to proceed in parallel with the RHIC II accelerator upgrades. The detector upgrades are overviewed and categorized as either *short term* or *mid-term* in [13]. The short term upgrades are projects that are already underway; for some, the construction is complete and commissioning is in progress.

Figure 9 illustrates the mid-term detector upgrade projects, which will be implemented as DOE construction projects with additional support and human resources provided by non-U.S. collaborators. Numerous participants in the PHENIX and STAR collaborations are actively collaborating on the detector upgrades: ≈ 30 universities and research labs in PHENIX, and ≈ 28 institutions in STAR. A number of new institutions have joined both collaborations with strong expressions of interest in design, construction, and new physics opportunities.

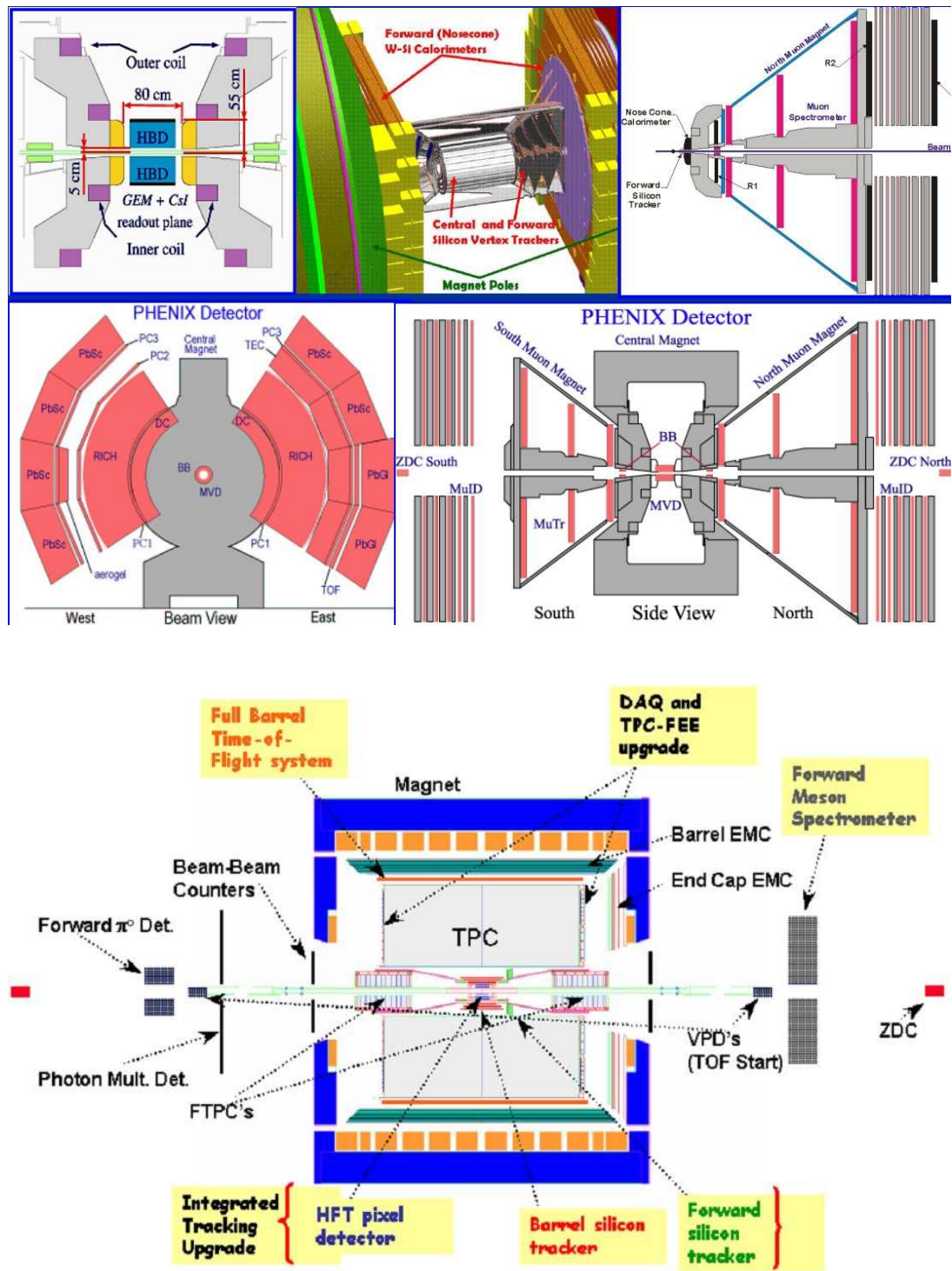


Figure 9. Schematic view of planned upgrades to (upper) PHENIX and (lower) STAR detectors.

Upgrades	High T QCD				Spin		Low x
	e+e-	heavy flavor	jet tomography	quarkonia	W	$\Delta G/G$	
PHENIX							
hadron blind detector (HBD)	x			o			o
Vertex tracker (VTX and FVTX)	x	x	o	o	x	x	o
μ trigger				o			
forward calorimeter (NCC)			o	o	o		x
STAR							
time of flight (TOF)		o	x	o			
Heavy flavor tracker (HFT)		x		x			
tracking upgrade		o			x	o	
Forward calorimeter (FMS)						o	x
DAQ		o	x	x	o	o	o
RHIC luminosity	o	o	x	x	o	o	o

Figure 10. Physics reach of planned PHENIX and STAR detector upgrades.

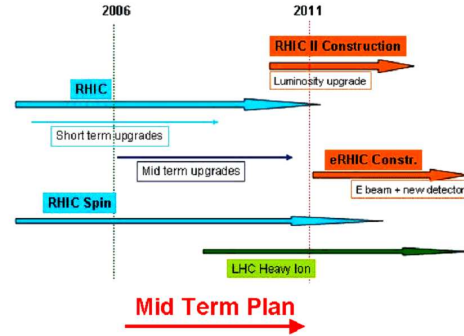


Figure 11. Current timeline projections for RHIC and its detectors.

Figure 10 shows the correlation of upgrades with physics topics. For each upgrade the table indicates those that are (x) essential for or (o) that enhance our ability to make each type of measurement. For a full overview see Chapter 5 in [13].

4. RHIC plan for the Long-Term: 2012-...

Figure 11 illustrates the evolution from the mid-term plan described above to the longer term. In addition to construction of RHIC II, plans for an electron relativistic heavy-ion collider (eRHIC) are also under way. Thirty years after QCD has been established as the Standard Model of the strong force, and despite impressive progress made in the intervening decades, understanding how QCD works in detail remains one of the outstanding issues in physics. Two of the many crucial open questions are: *What is the gluon momentum distribution in the atomic nucleus?* and *How is the spin structure of the nucleon understood to arise from the quark and gluon constituents?* A recent publication [14] gives a comprehensive overview of the science case for an EIC and the developing plans for eRHIC at Brookhaven and an alternative approach for an electron light-ion collider (eLIC) at Thomas Jefferson National Laboratory (Jlab).

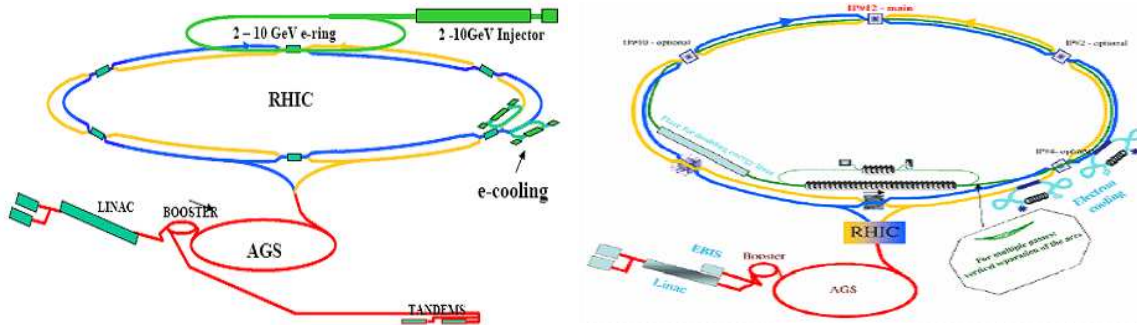


Figure 12. Layouts of (left) ring-ring and (right) linac-ring designs for eRHIC.

Figure 12 shows two approaches to eRHIC that are currently under consideration and development. The ring-ring design (left) centers on a 10 GeV lepton storage ring that intersects one of the RHIC ion beams at one of the interaction regions (IRs). The linac-ring design (right) uses a fresh electron beam bunch for each collision and so the tune shift limit on the electron

beam is removed. The ELIC proposal at Jlab [15] would use polarized 5 to 7 GeV electrons in an upgrade of the present CEBAF accelerator and a new 30 to 150 GeV ion storage ring.

In summary, the ability to fully investigate the compelling science questions arising from early discoveries at RHIC depends crucially on the RHIC II facility upgrades and on the completion of the ongoing detector upgrades to PHENIX and STAR. The luminosity upgrade is critical for the heavy-ion program to allow access to far more powerful probes that involve inherently low cross sections. A large area of the QCD phase diagram will be opened to investigation and the upgrades will allow us to vary the collision energy and colliding beam species many times in a single year - while still accumulating large integrated luminosities. For the polarized proton program, the factor of three increase in luminosity is essential for reaching the full potential of the sea quark polarization and transverse spin measurements, and will improve the precision of the gluon polarization measurements. An electron-ion collider will dramatically extend our understanding of the spin structure of the proton and will explore *terra incognita* in our understanding of the properties of quarks and gluons in nuclei [14].

Acknowledgments

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